Institute of High Energy Physics
Chinese Academy of Sciences

CEPC Circular Electron Positron Collider

The lattice design of SppC collider ring

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SppC parameters

	75 TeV	125 TeV	Unit
General design parameters			
Circumference	100	100	km
Beam energy	37.5	62.5	TeV
Lorentz gamma	39979	66631	
Dipole field	12	20	T
Dipole curvature radius	10415.4	10415.4	m
Arc filling factor	0.78	0.78	
Total dipole magnet length	65.442	65.442	km
Total arc length	83.9	83.9	km
Number of long straight sections	8	8	
Total length of straight sections	16.1	16.1	km
Energy gain factor in collider rings	17.86	19.53	
Injection energy	2.1	3.2	TeV
Number of IPs	2	2	
Revolution frequency	3.00	3.00	kHz
Physics performance and beam parameters			
Initial luminosity per IP	1.0×10^{35}	4.3×10^{34}	$cm^{-2}s-1$
Beta function at collision points	0.75	0.5	m
Circulating beam current	0.73	0.19	A
Nominal beam-beam tune shift limit per IP	0.0075	0.015	
Bunch separation	25	25	ns
Number of bunches	10080	10080	
Bunch population	1.5×10^{11}	4.0×10^{10}	
Accumulated particles per beam	1.5×10^{15}	4.0×10^{14}	
Normalized RMS transverse emittance	2.4	1.2	μm
Beam life time due to burn-off	14.2	8.1	hours
Total inelastic cross section	147	161	mb
Full crab crossing angle[1]	110	73	μrad
RMS bunch length	75.5	60	mm
RMS beam spot size at IP	6.8	3.0	μm
Stored energy per beam	9.1	4.0	GJ
SR power per beam	1.1	2.2	MW
SR heat load at arc per aperture	12.8	26.3	W/m
Energy loss per turn	1.48	11.4	MeV

[1] Crab cavities are used to recover the luminosity loss.

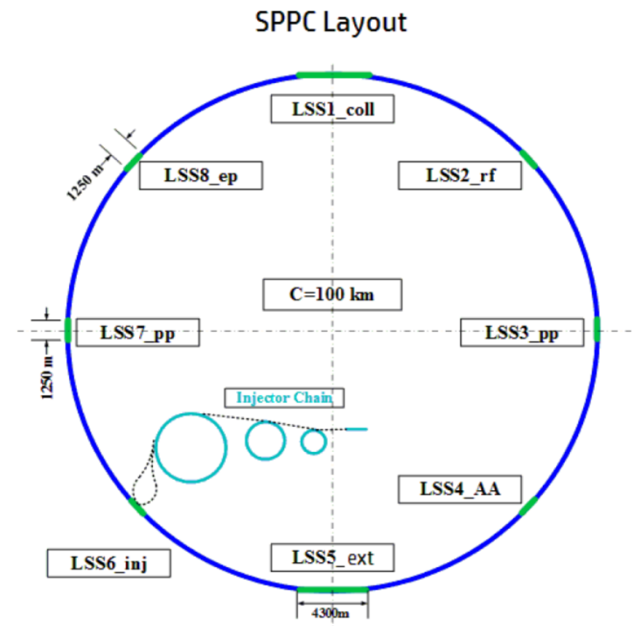
IP w/o crossing angle applied in this lattice

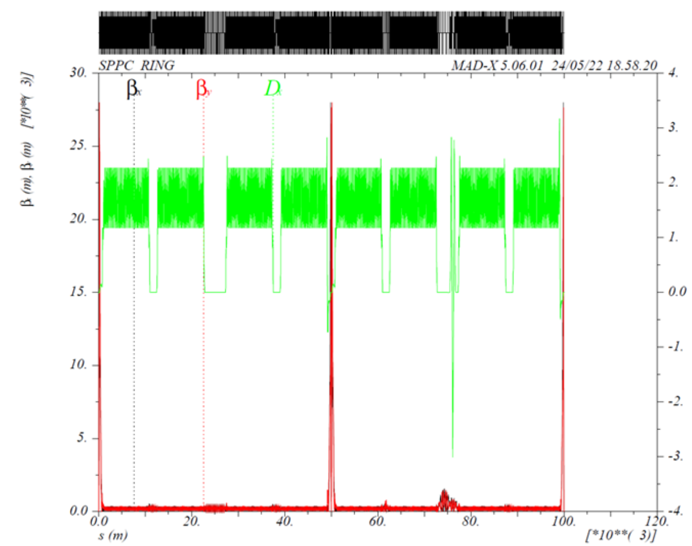
Jingyu Tang et al, Snowmass 2021 White Paper AF4 - SPPC

SppC lattice design

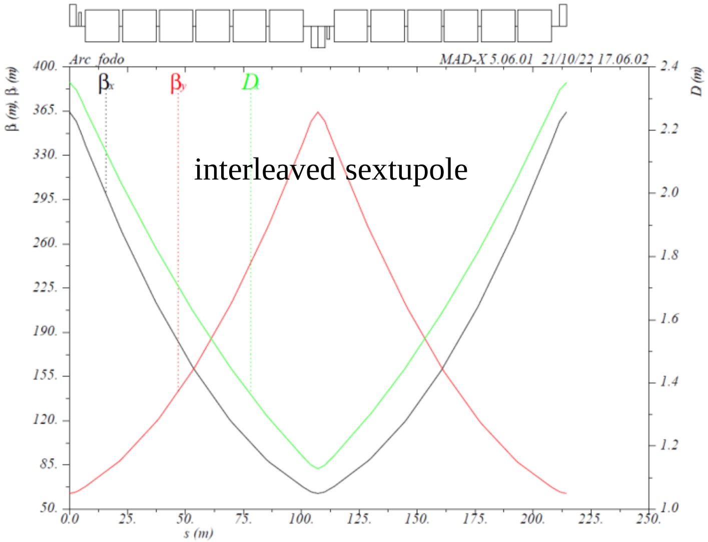
- Compatible with CEPC, 100km, 2 IPs
- 8 arc sections
  - 2-in-1 yoke-sharing magnets
  - both interleaved and non-interleaved sextupoles studied
- 4 short straight sections
  - RF region, dual-harmonic RF system (800 and 400 MHz)
  - injection section after injection chain
  - e-p collision with CEPC
- 2 long straight sections
  - collimation section for both betatron and momentum
  - extraction section
- 2 interaction regions
  - anti-symmetric interaction region
  - chromaticity corrected with arc sextupoles

More realistic lattice for RF and e-p regions are not implemented in this lattice yet.

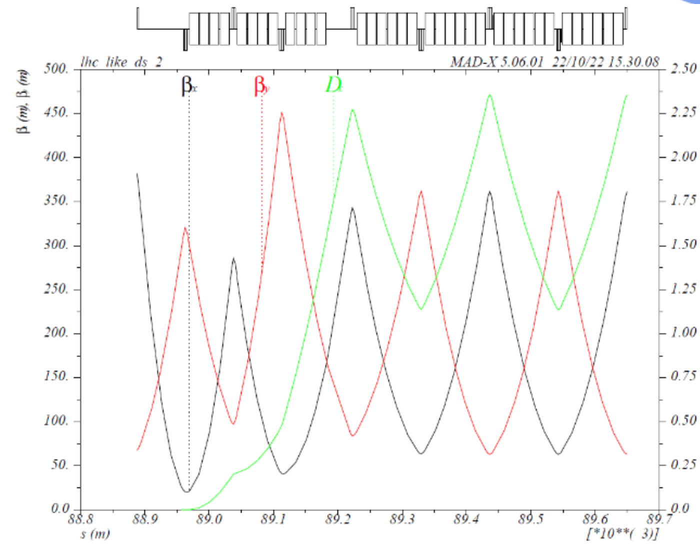




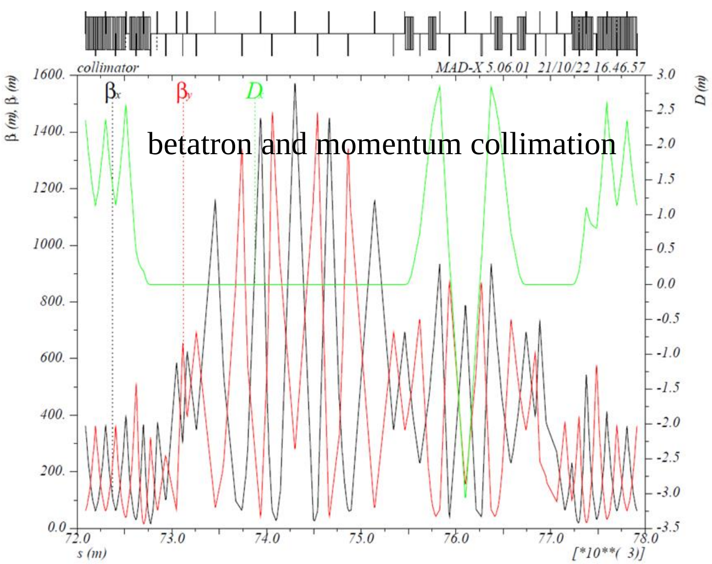
Lattice optics



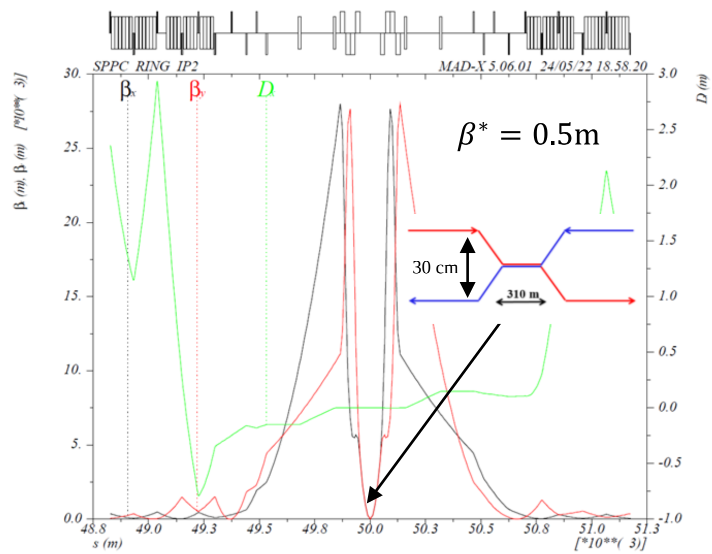
Arc FODO cell



Dispersion suppressor



Collimation section



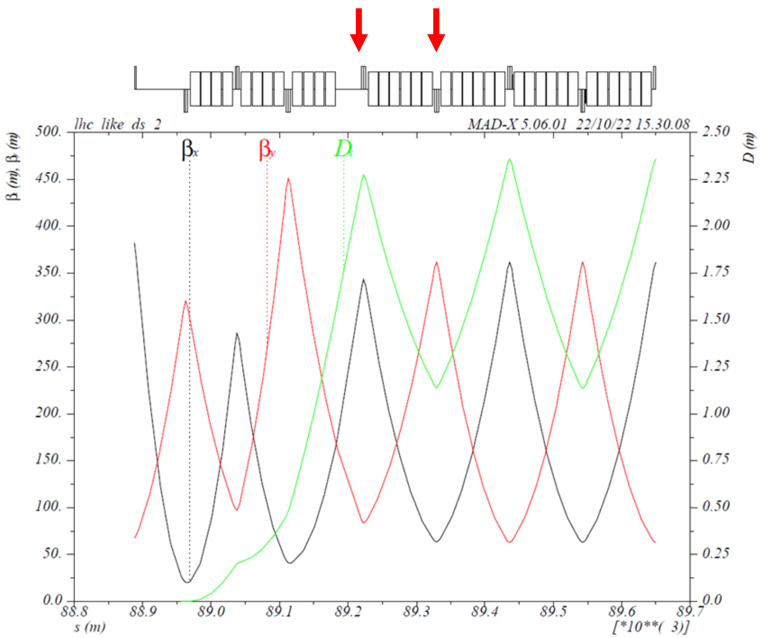
Interaction region

Nonlinearity optimization with interleaved sextupoles

- To get better nonlinearity cancellation for 90°/90° FODO lattice.
  - Remove two sextupoles at the red arrow in DIS to make the amount of sextupoles in arc region to be an integer multiple of 4*
- Adjust the phase advance between different sections to optimize the 2nd order chromaticity and W-functions.
- Match the working point of the whole ring to (0.12, 0.13) in consideration of beam-beam interaction.

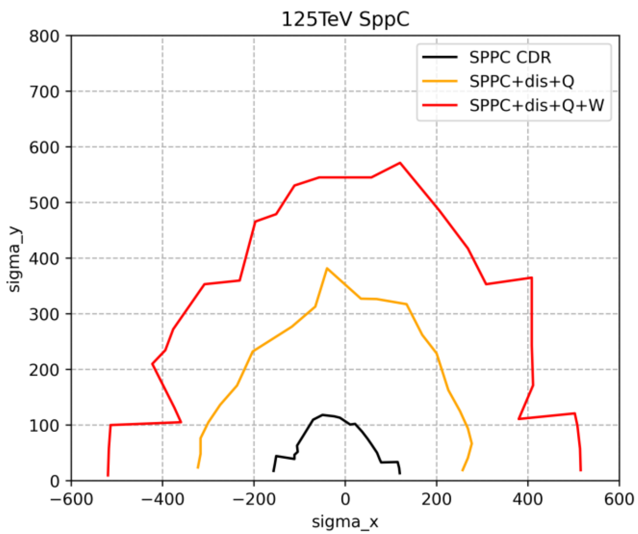
$$W_x = \sqrt{a_x^2 + b_x^2}$$

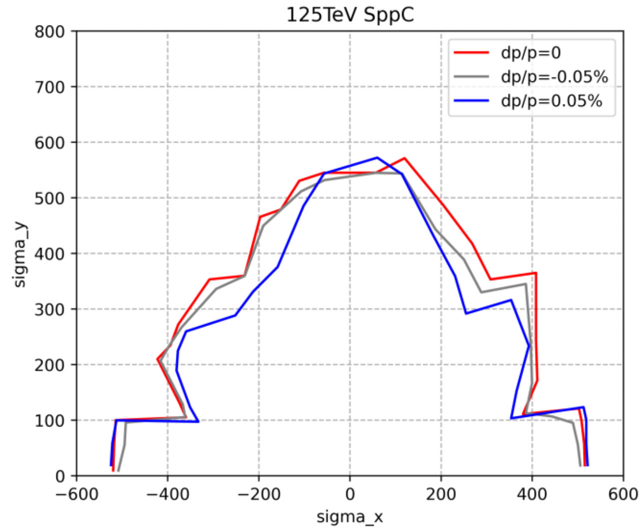
$$b_x = \frac{1}{\beta_x}\frac{\partial \beta_x}{\partial p_t} \qquad a_x = \frac{\partial \alpha_x}{\partial p_t} - \frac{\alpha_x}{\beta_x}\frac{\partial \beta_x}{\partial p_t}$$



*Yiwei Wang, International Symposium on Higgs Boson and Beyond Standard Model Physics, August 15-19, 2016.

Nonlinearity optimization with interleaved sextupoles





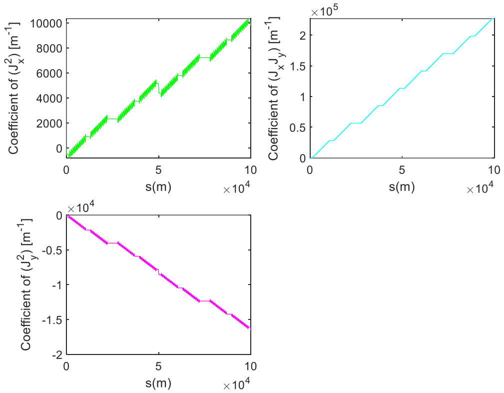
$\sigma_x = 0.035$ mm
$\sigma_y = 0.084$ mm
$\varepsilon_n = 1.22$ µm

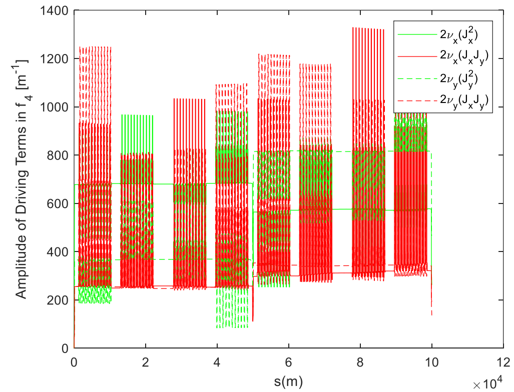
Working point	SPPC CDR (0.109,0.459)	SPPC+dis+Q (0.12,0.13)	SPPC+dis+Q+W (0.12,0.13)
dQx/dJx	-0.0824	-0.0199	-0.0009
$dQx/dJy(dQy/dJx)$	-0.0317	-0.0268	-0.0169
dQy/dJy	-0.0254	0.0050	0.0039
$dQx002$	0.0002	0.0016	0.0009
$dQy002$	0.0180	0.0012	0.0013
$dQx003$	0.0005	0.0007	0.0002
$dQy003$	0.0006	0.0007	0.0003
IP2 W_x	148	134	121
IP2 W_y	1873	300	104
IP4 W_x	292	279	91
IP4 W_y	1938	170	151

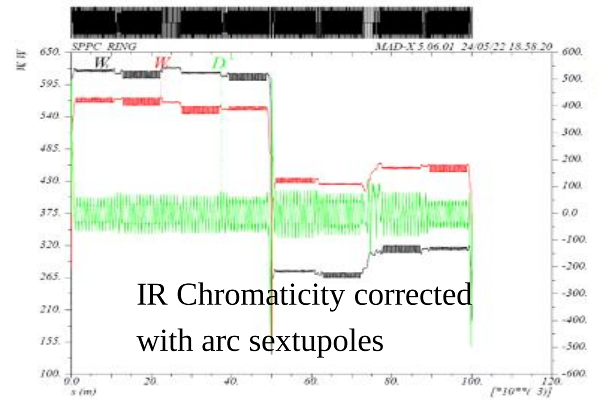
Comparison of some key nonlinearities for different optimization steps, with 400 σ_x and 400 σ_y, 0.05% energy spread, $\varepsilon_n = 1.22$µm. 'dis': remove two sextupoles in DIS; 'Q': match working point; 'W': match the phase advances between different sections.

Nonlinearity optimization with interleaved sextupoles

Aberration analysis performed by LEGO code

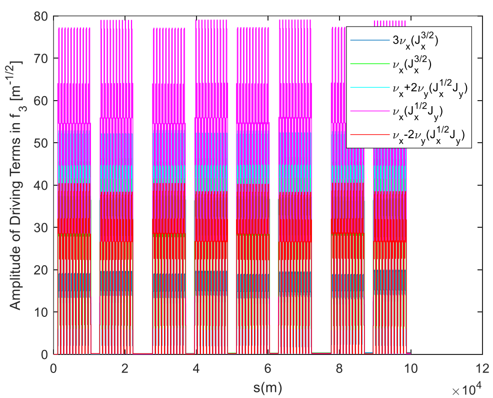


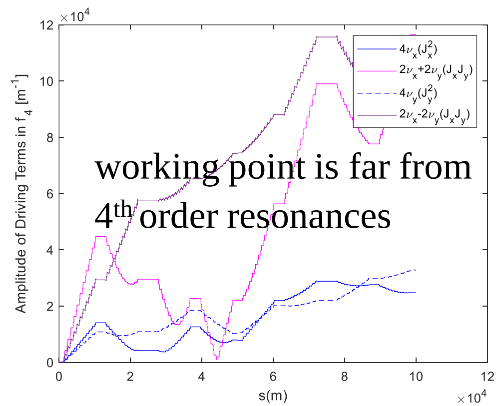




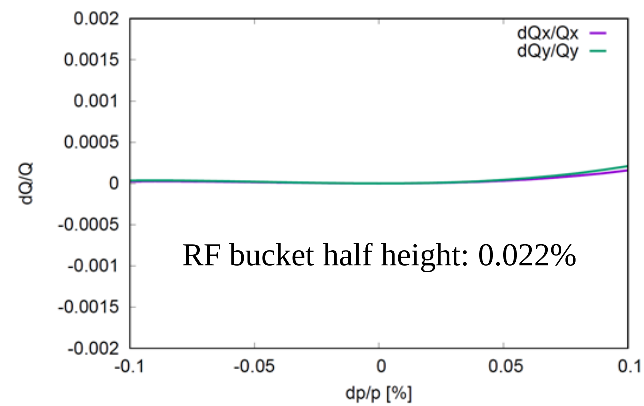
IR Chromaticity corrected with arc sextupoles

W-functions





working point is far from 4^{th} order resonances



RF bucket half height: 0.022%

Amplitude-dependent tune shift and 2^{nd}, 3^{rd}, 4^{th} order RDTs along the ring

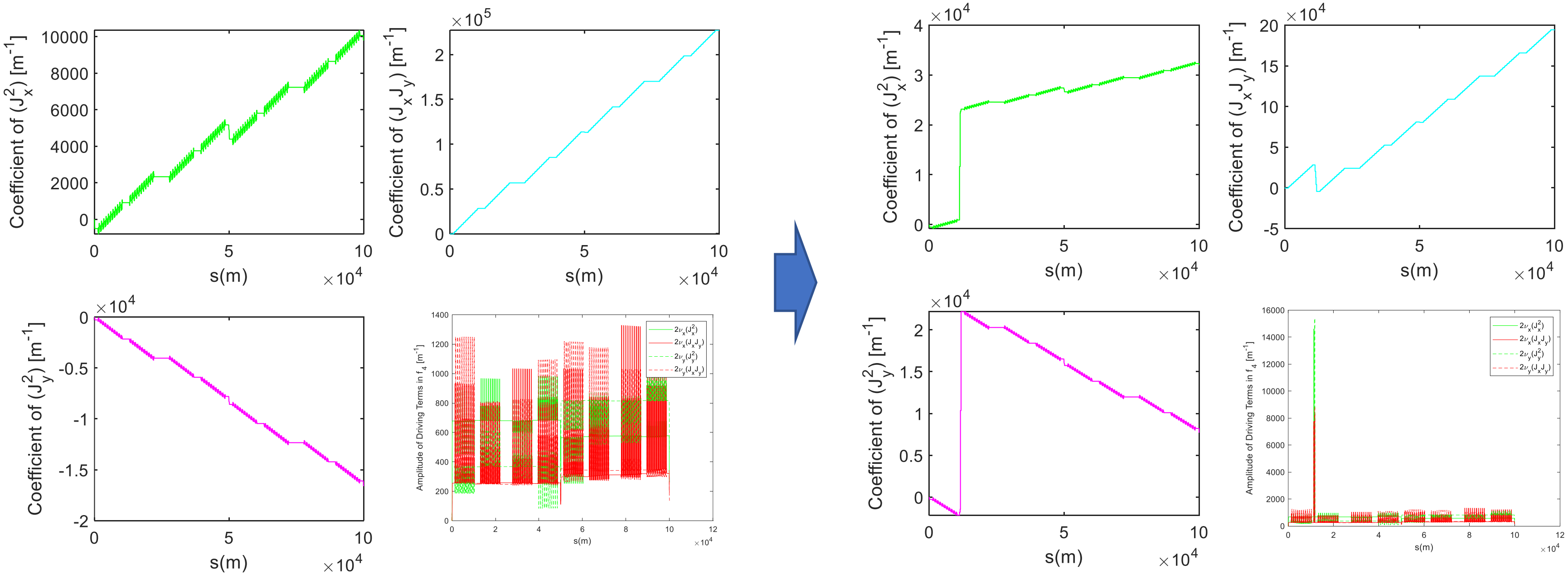
Chromaticity

Further optimization of the tune shift

- Octupoles are installed for tune shift correction.
- Hamiltonian of Octupole*:

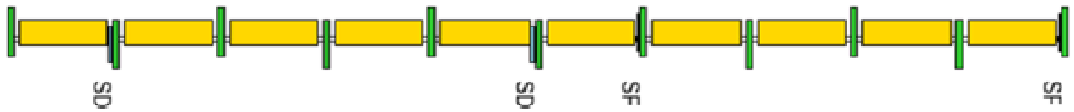
*Moohyun Yoon 1998 *Jpn. J. Appl. Phys.* **37** 3626

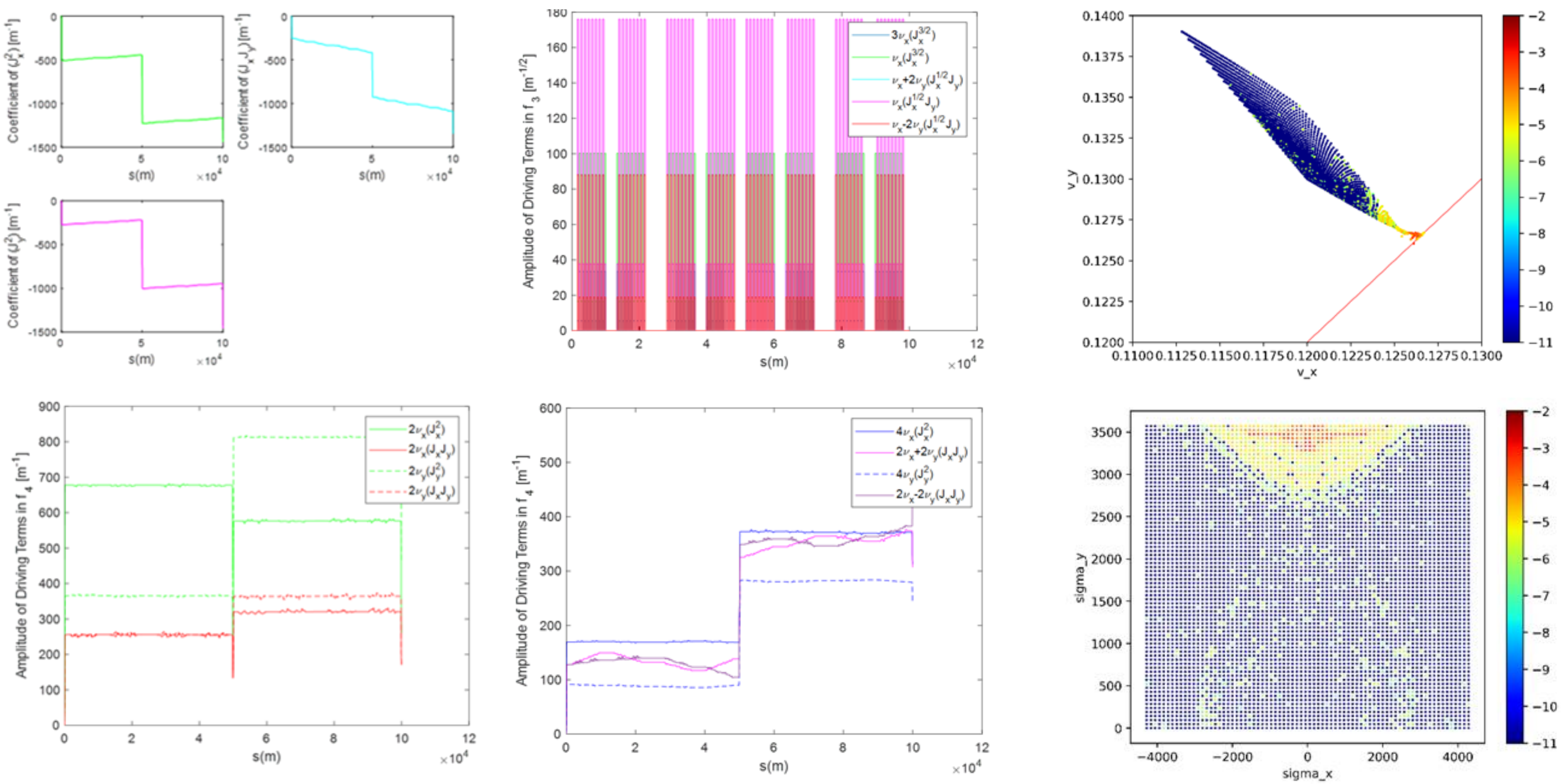
- $\overline{V}(I,\phi;s)=\frac{B'''}{48B\rho}\left[\beta_x^2 J_x^2(\cos 4\phi_x+4\cos 2\phi_x)-6\beta_x\beta_y J_x J_y\{\cos 2(\phi_x+\phi_y)+\cos 2(\phi_x-\phi_y)+2\cos 2\phi_x+2\cos 2\phi_y\}+\beta_y^2 J_y^2(\cos 4\phi_y+4\cos 2\phi_y)\right].$
  - mainly care about 2nd order RDTs as the working point (0.12, 0.13) is far from 4th order and coupling resonances.
  - Pairs of octupoles with equal strength and phase advance $\Delta\phi_x=\Delta\phi_y=90°$ works.
  - Currently two pairs of octupoles are used. Further work is under going.



Nonlinearity optimization with non-interleaved sextupoles

- 5 FODO cells per period. Most nonlinearities are cancelled in 4 periods and the tune shifts are significantly reduced compared with the interleaved scheme.
- Since the number of sextupoles is less than interleaved scheme, the sextupoles in arc will be stronger, thus the length of sextupoles is doubled to 1m to weaken the sextupoles.

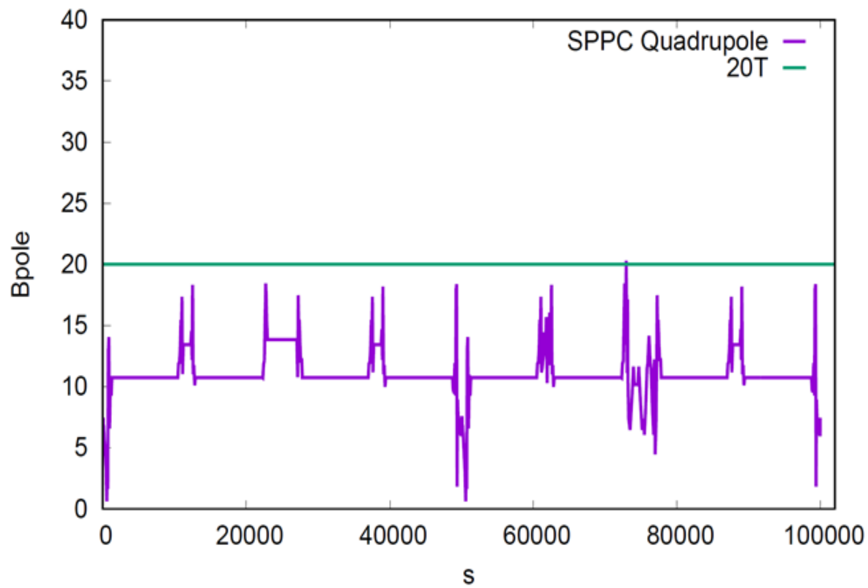




Dynamic aperture: larger than $3000\sigma_x$ *$3000\sigma_y$, 245mm*245mm with $\beta_{FODO,max} = 365$m and $\varepsilon_n = 1.22$μm

Magnet gradient and strength

- The aperture diameters of magnets are divided into two groups*:
  - in the insertions or matching sections, D = 60mm;
  - in the arcs, D = 45mm.
- All the B_{pole} of quadrupoles are below the limit of 20T.



Magnet type	Length	Gradient	Strength of B_{pole}
Main dipole ($\phi = 45mm$)	14.45192 m		20 T
Main quadrupole ($\phi = 45mm$)	6 m	$477\ \mathrm{T \cdot m^{-1}}$	10.74 T
Strongest quadrupole ($\phi = 60mm$)	6 m	$676\ \mathrm{T \cdot m^{-1}}$	20.28 T
Interleaved sextupole ($\phi = 45mm$)	0.5 m	$6711\ \mathrm{T \cdot m^{-2}}$ / $13588\ \mathrm{T \cdot m^{-2}}$	1.70 T / 3.44 T
Non-interleaved sextupole ($\phi = 45mm$)	1 m	$9115\ \mathrm{T \cdot m^{-2}}$ / $18576\ \mathrm{T \cdot m^{-2}}$	2.31 T / 4.70 T
Octupole for correction ($\phi = 60mm$)	thin-lens	$254371\ \mathrm{T \cdot m^{-3}}$ / $279808\ \mathrm{T \cdot m^{-3}}$	1.14 T / 1.26 T

*CEPC CDR

Error definition

- Errors defined for all dipoles, quadrupoles and BPMs in lattice;

Element	Error	Error desc.	Units	Main dipole	Separation dipole
Dipole	$\sigma(\psi)$	roll angle	mrad	0.5	1
	$\sigma(\delta B/B)$	random b1	%	0.1	0.05
	$\sigma(\delta B/B)$	random b2	10^{-4} units	0.92	0.1/1.1
	$\sigma(\delta B/B)$	random a2	10^{-4} units	1.04	0.1/0.2
	$\sigma(\delta B/B)$	uncert. a2	10^{-4} units	1.04	TBD
				Main quadrupole	IR triplet / other
Quad.	$\sigma(x), \sigma(y)$		mm	0.5	0.2/0.5
	$\sigma(\psi)$	roll angle	mrad	1	TBD/0.5
	$\sigma(\delta B/B)$	random b2	%	0.1	TBD/0.05
BPM	$\sigma(x), \sigma(y)$		mm	0.3	0.3
	$\sigma(\text{read})$		mm	0.2	0.05/0.2

*Reference radius of field error is 17mm.

Ref: D.Boutin et al, optic corrections for Fcc-hh, IPAC2019

Error effects evaluation

- For each kind of errors, RMS values of the following observables along the ring are calculated: beta-beating, residual orbit, and normalized off-momentum close orbit distortion.

- The alignment errors of quadrupoles on both planes seem to be most impactful to the machine performance, but still not severe.

with non-interleaved sextupole lattice

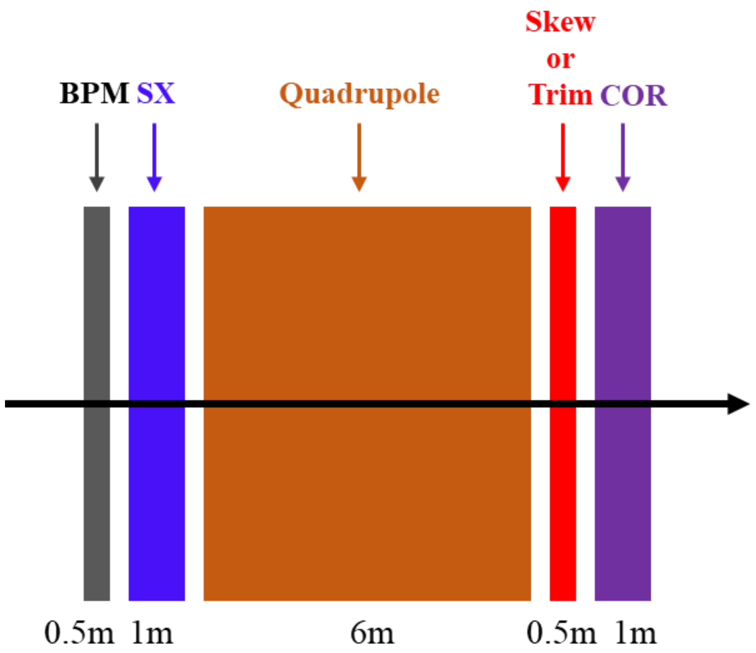
Error type	$\frac{\Delta\beta_x}{\beta_{ref}}_{rms}$ [%]	$\frac{\Delta\beta_y}{\beta_{ref}}_{rms}$ [%]	Δx_{rms} [mm]	Δy_{rms} [mm]	$\frac{\Delta D_x \delta_E}{\sqrt{\beta_{ref}\varepsilon_x}}_{rms}$	$\frac{\Delta D_y \delta_E}{\sqrt{\beta_{ref}\varepsilon_y}}_{rms}$
MB_b1	8.3	9.7	6.1	/	4.6	/
MB_b2	5.6	7.4	/	/	0.8	/
MB_a2_random	4.2	3.2	/	/	0.1	0.2
MB_a2_system	2.0	0.9	/	/	0.1	0.3
MB_psi	2.2	2.2	0.5	6.5	0.7	7.5
MQ_b2	5.0	4.7	/	/	0.2	/
MQ_dx	96.2	101.0	78.4	/	127.9	/
MQ_dy	14.2	13.8	4.5	25.9	11.0	40.3
MQ_psi	2.8	2.5	/	/	0.07	0.5

* $\delta_E = 2 \times 10^{-4}$, $\varepsilon_n = 1.22\mu m$.

Correction scheme

Ref: LHC-report-501

- All quadrupoles are equipped with a **BPM** and an orbit corrector (COR). And quadrupole correctors (skew or trim) can be inserted around the quadrupole.
    - Coupling correction is performed with families of 8 skew quadrupoles around the middle of each arc, each corrector separated by 90° phase advance.
    - Tune correction is performed with two families of 8 trim quadrupoles at the beginning and end of arc sections, each corrector separated by 45° phase advance.



Error correction

preliminary

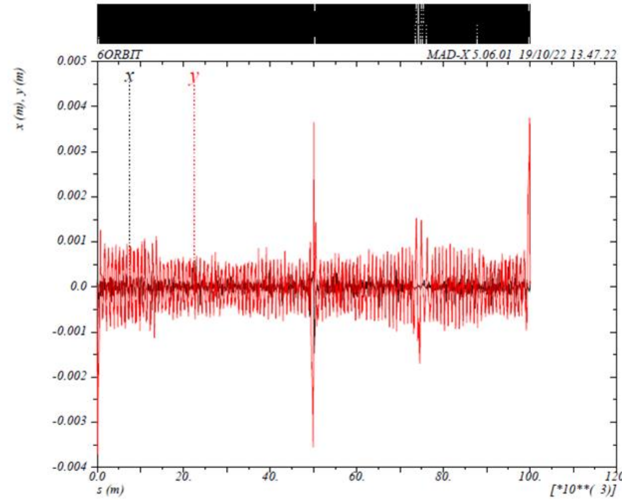
with non-interleaved sextupole lattice

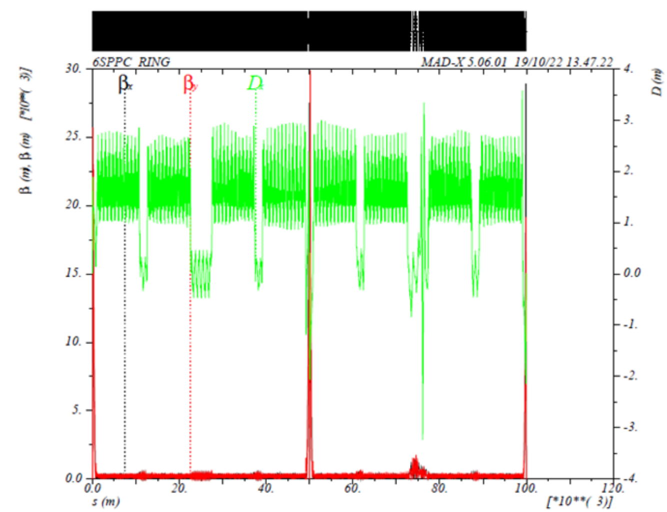
The correction is performed by MADX code:

1. Global orbit correction, to avoid twiss failing after errors are applied;
2. Analytic correction of the linear coupling;
3. Global orbit correction;
4. Tune correction and chromaticity correction.

Results with one seed

	Correction results
Horizontal orbit	1.55 mm
Vertical orbit	4.13 mm
Horizontal angle	20 μrad
Vertical angle	99 μrad
Hori. beta-beating	22.9%
Vert. beta-beating	61.7%
Hori. disp.-beating	$0.039\ m^{\frac{1}{2}}$
Vert. disp.-beating	$0.062\ m^{\frac{1}{2}}$





Results are not satisfactory but not bad, and the correction of beta-beating and dispersion-beating $\Delta D/\beta_{ref}$ needs further investigation.

CEPC-SppC compatibility

- Geometry compatibility of the CEPC and SPPC
  - The SPPC will share the tunnel of CEPC as much as possible.
  - The SPPC locates outside of CEPC
  - In the 8 arc regions and 4 short straight sections, two machines share the tunnel (distance of machine centers=3.5m)
  - In the 4 long straight sections, the SPPC will bypass the CEPC (distance of machine centers at IPs=23m as the big size of CEPC and SPPC detectors)
    - IP1 and IP3 for CEPC interaction and SPPC collimation, IP2 and IP4 for CEPC RF and SPPC interaction

Tunnel in the ARC

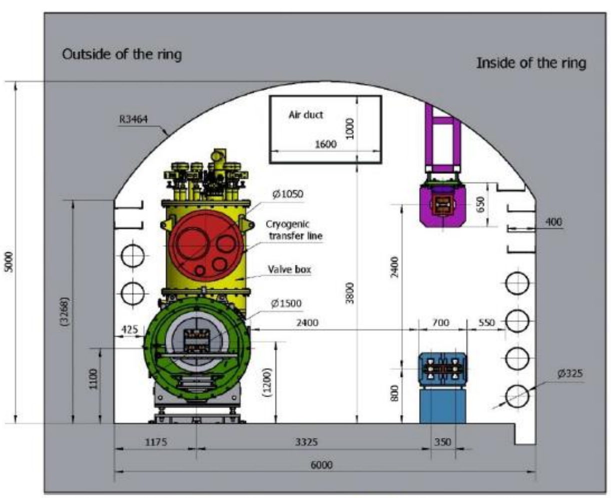
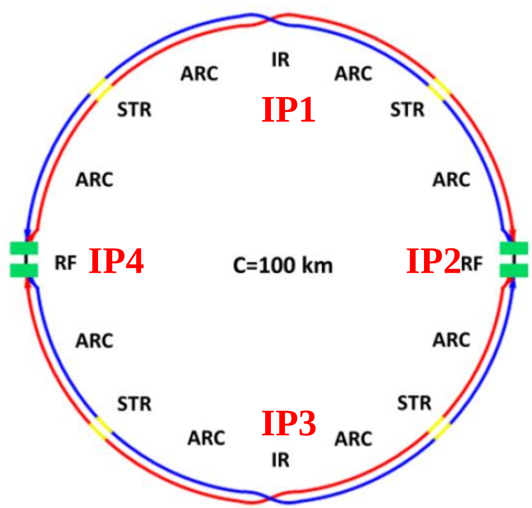
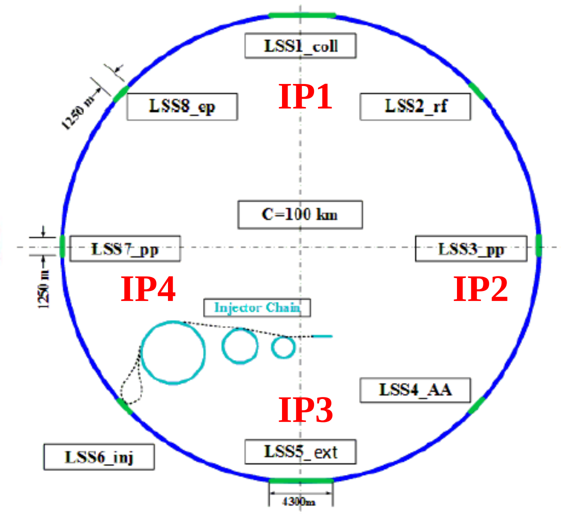


Figure 2.1: Tunnel cross section in the arc region

CEPC Layout



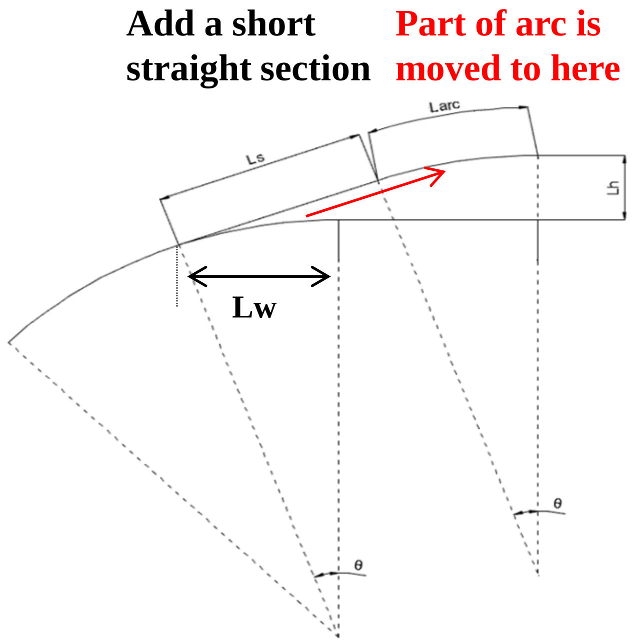
SPPC Layout



Geometry compatibility at IP2 and IP4

- For IP2 and IP4, the SPPC interaction regions are much shorter than the CEPC RF regions. SPPC can bypass CEPC within a reasonable length using baseline bend (20T).
- Bypass Scheme
  - add a short straight section at the end of ARC
  - Lw is the additional length for bypass which is 0.28km for distance of 23m
  - Total length of bypass at IP2 or IP4 is 4 km

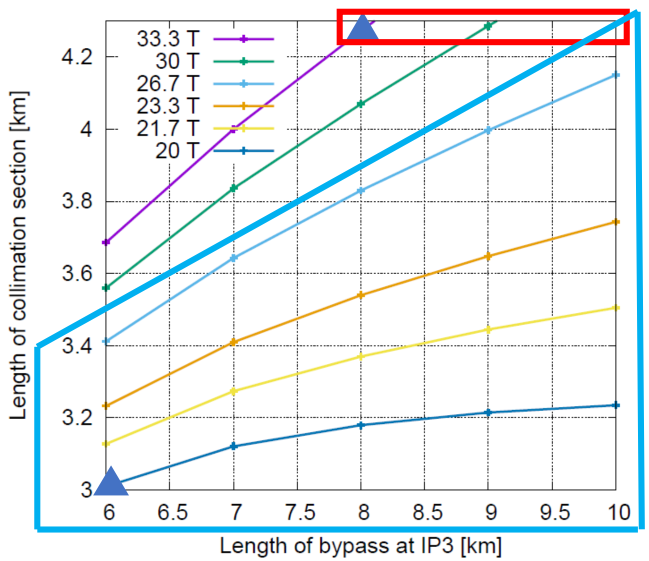
	IP2 & IP4
SPPC	1.25 km
CEPC	3.42 m

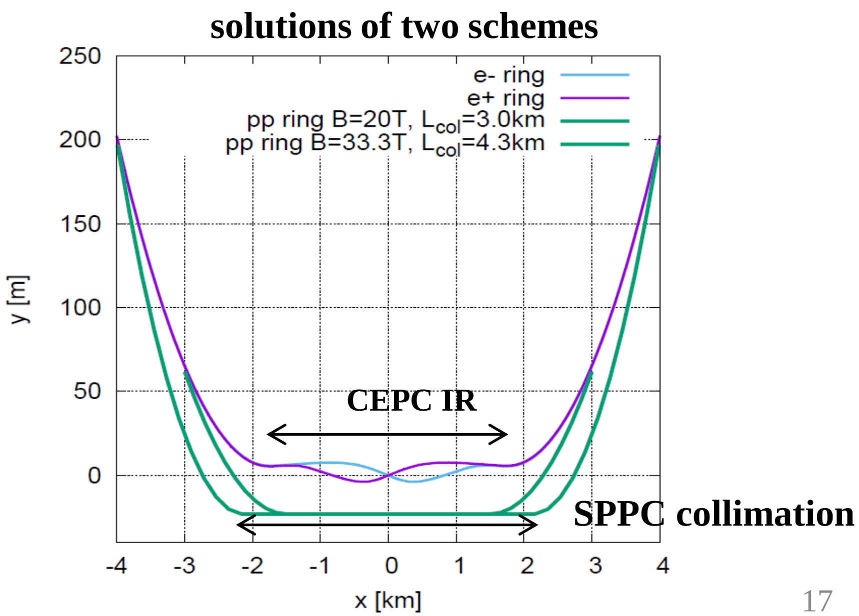


Geometry compatibility at IP1 and IP3

Possible bypass Schemes

- bypass within a reasonable length using much stronger bend
    - Lcol = 4.3 km, 28.3 T ≤ B ≤ 33.3 T, 8km ≤ length of bypass ≤ 10 km
- bypass within a reasonable length using a bit stronger bend which need to shorten the length of SPPC collimation length thus a different design of SPPC collimation section
    - 3 km ≤ Lcol < 4.3 km, 20T ≤ B < 28.3T, 6km ≤ length of bypass ≤ 10 km





Summary

- The design of SppC lattice for $E_{cm} = 125\text{TeV}$ has been studied. Nonlinearity optimization has been performed.
  - Interleaved sextupole scheme: DA ~ 400 σ_x * 400 σ_y w/o errors
  - Non-interleaved sextupole scheme: DA ~ larger than 3000 σ_x * 3000 σ_y w/o errors
- Error tolerances of SppC collider ring lattice have been evaluated.
- Preliminary error correction scheme has been applied to the collider ring with non-interleaved sextupoles. It still needs more investigation as well as the correction of beta-beating and dispersion-beating $\Delta Dx/\beta_{ref}$.
- A preliminary study on geometry compatibility of CEPC and SPPC was performed.